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Review article

The role of multimodal imaging in emergency vascular conditions: The journey from diagnosis to hybrid operating rooms

*Elda Chiara Colacchio**, *Mariagiovanna Berton, Francesco Squizzato, Mirko Menegolo, Michele Piazza, Franco Grego, Michele Antonello*

Department of Cardiac, Thoracic, Vascular Sciences and Public Health, Vascular and Endovascular Surgery Clinic, Padova University, School of Medicine, Via Nicolò Giustiniani 2, 35128 Padova, Italy

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ABSTRACT

Multimodal imaging is the incorporation of two or more imaging modalities during the same examination, and it has both diagnostic and treatment applications. The use of image fusion for intraoperative guidance in endovascular interventions is being extended increasingly to the field of vascular surgery, especially in the context of hybrid operating rooms. The aim of this work was to perform a review and narrative synthesis of the available literature in order to report on current applications of multimodal imaging in diagnosis and treatment of emergent vascular conditions. Of 311 records selected in the initial search, 10 articles were included in the present review: 4 cohort studies and 6 case reports. The authors have presented their experience in treating ruptured abdominal aortic aneurysms; aortic dissections; traumas; standard endovascular aortic aneurysm repair, with or without deterioration of renal function; and complex endovascular aortic aneurysm repair, and reported on the long-term clinical results. Although the current literature about multimodal imaging application in emergency vascular conditions is limited, this review highlights the potential of image fusion in hybrid angio-surgical suites, especially for diagnosing and performing treatment in the same operating room, avoiding patient transfer, and allowing procedures with zero or low-dose contrast mean.

1. Introduction

Many imaging modalities can be employed to diagnose and treat pathologies, although the information provided is not always superimposable and every device has its own limitations.

Digital subtraction angiography (DSA) has traditionally been considered the “gold standard” for both diagnosis and treatment of vessel pathology, yet it provides two-dimensional (2D) information only and is an invasive tool. Computed tomography angiography (CTA) is consistently less invasive and it provides fast cross-sectional images with high spatial definition, yet the resolution of soft tissues is not optimal [1] and the radiation dose is not neglectable. Magnetic resonance imaging and magnetic resonance angiography are not often used routinely in vascular surgery because of their long imaging times and high costs, plus there are difficulties

* Corresponding author.
E-mail address: eldachiaracolacchio@gmail.com (E.C. Colacchio).

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in providing three-dimensional (3D) reconstruction with the current available software; yet, they do not have limitations in terms of tissue penetration and they provide high resolution of soft tissues [1].

Multimodal imaging (MMI) is defined as the incorporation of two or more imaging modalities during the same examination in order to produce radiologic clichés of the same patient with different information content, possibly overcoming limitations of single examinations. Classical applications of MMI are the combination of computed tomography (CT) and positron emission tomography (PET) or PET and single-photon emission computed tomography, providing both functional and anatomic information [2].

MMI has both diagnostic and treatment applications, and its use has spread to the field of vascular surgery with the concept of image fusion (IF) for intraoperative guidance in endovascular interventions. In fact, without IF, information from preoperative imaging is mentally registered by the operators, and radiologic data are integrated via a system of landmarks. IF application in vascular surgery consists of superimposing the 3D reconstruction of the arterial axes affected by pathology with live fluoroscopy [3]. 3D models are obtained via preoperative CTA or magnetic resonance angiography or periprocedural contrast-enhanced cone-beam CT (CBCT). MMI is usually performed in a hybrid operating room (HOR), a highly specialized angio-surgical suite that allows diagnosis and endovascular and surgical treatments in the same location, thus avoiding patient displacement, which could ultimately lead to a loss of time, especially in emergency cases.

The aim of this work was to present the current state-of-the-art applications of MMI in the diagnosis and treatment of emergent vascular conditions.

2. Materials and methods

2.1. Search strategy

We relied on the Preferred Reporting Items for Systematic Review and Meta-Analyses guidelines [4] to perform this review and narrative synthesis of the literature. An electronic research was conducted in December 2022 of Medline and Embase databases, using the following terms: “multimodal imaging,” “multimodality imaging,” “emergency,” “urgent,” “vascular surgery,” “endovascular surgery,” “image fusion,” “hybrid room” and “hybrid angio-surgical suite.” We selected only articles in English and published in the last 10 years. Exclusion criteria were articles discussing pathology of arterial districts different from those pertaining to vascular surgery, such as those treated with cardiac surgery, coronary revascularizations, and neurosurgery or neuroradiology. Furthermore, we excluded guidelines, reviews, systematic reviews and metanalysis, and comments to other articles. Because current literature on the investigated field is limited, we decided not to exclude case reports.

2.2. Study selection and eligibility criteria

A reference management software (Mendeley Desktop, version 1.19.8; Mendeley Ltd) was used to import articles and remove duplicates. We performed an initial screening of articles by title and abstract, and finally by full text (Fig. 1). All steps of the selection were performed independently by two researchers (E.C.C., M.B.); discrepancies and disagreements were resolved by means of discussion.

We selected articles that discussed the use of IF in the diagnosis and treatment of emergent vascular conditions, such as ruptured aortic aneurysms, symptomatic or infected aortic aneurysms, and aortic dissections. The final selection included both case reports and retrospective analyses. Articles analyzing cases performed in an elective setting only were excluded from the review, and articles discussing interventions in both an elective context and an urgent context were included.

2.3. Data synthesis

Overall, we collected selected baseline information, such as author, year of publication, type of article, and overall number of patients (specifying how many were treated in an emergency setting). We detailed the type of fusion imaging, whether there was a combination of preoperative CTA and intraoperative DSA, or preoperative CTA and perioperative CBCT. Given the large heterogeneity of the available literature, we performed a narrative synthesis of all articles. Results varied from a simple description of cases performed, to comparison studies in which data for patients operated in an HOR with fusion imaging were compared with data for patients operated in a classic suite with a portable mobile C-arm. Reported intraprocedural data were contrast medium volume, procedure time, and dose-area product (DAP; expressed in Gy-cm^2). Clinical outcomes included primary technical success and major adverse events. One article also analyzed the accuracy of endograft deployment by measuring the distance between the lower renal artery and the parallax of the proximal gold markers of the endograft (LwRA/EDG) [5]; another also discussed long-term clinical outcomes, such as target vessel instability, graft instability, reinterventions, occlusion of target vessels or limbs, overall mortality, and aortic-related death during follow-up [6].

3. Results

3.1. Article selection

The initial research included 311 records identified through a search of PubMed (n = 207) and Embase (n = 104) databases, and 270 were screened based on title and abstract. Twenty-two full-text articles were examined and 10 articles were finally included in the present review—4 observational studies and 6 case reports (Fig. 1).

In all of the case reports, authors discussed the management of patients treated in an emergent setting. Five of these exposed a single patient treatment each, and in one report the management of 3 different patients was discussed.

Four cohort studies analyzed a series of patients, further divided in two groups based on whether the intervention was performed in a standard operating room (OR) or in an HOR with IF.

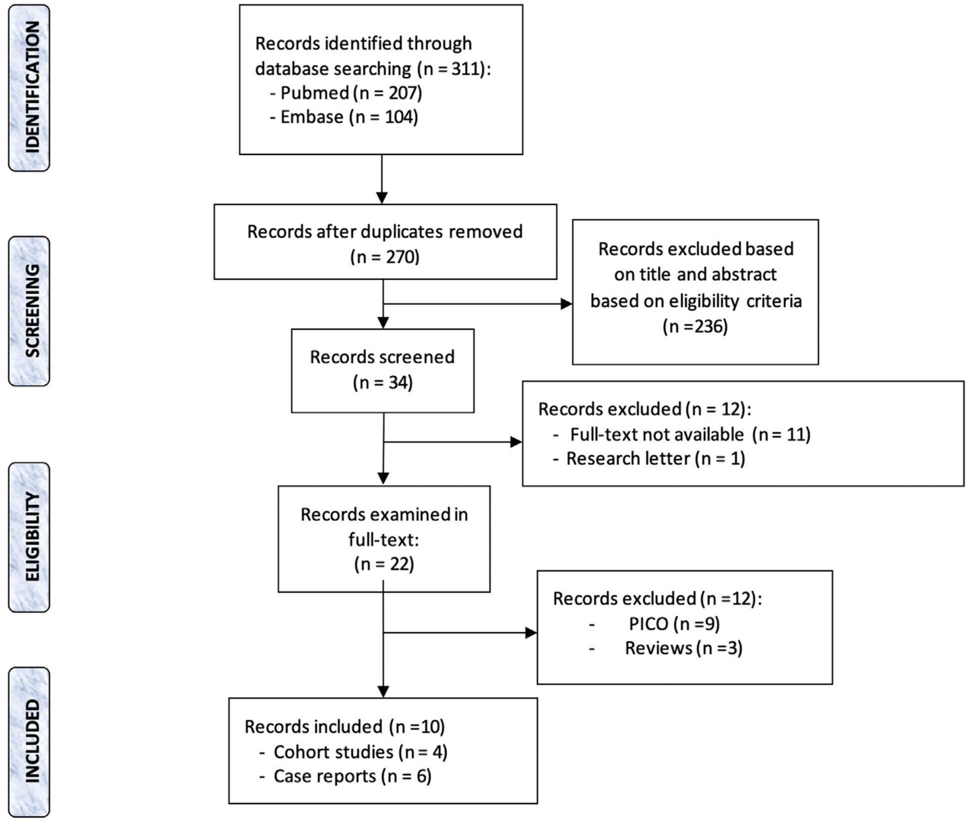

Fig. 1 – Screening process and selection of reviewed articles [4]. All not-available texts were related to abstracts presented at scientific meetings and subsequently published without full text. PICO, population, intervention, comparison, outcome.

Table 1 – Main features of included case reports.

Study, first author	Year	Diagnosis	Diagnostic imaging[a]	Treatment
Ziza [13]	2015	rAAA + renal impairment	CTA	EVAR
Zeng [12]	2016	AAP, AAA with imminent rupture, symptomatic AAA	CTA	PMFSG
Touma [9]	2018	T1aEL	CTA	Triple in-situ laser fenestration
Masana Llimona [7]	2020	rAAA + AKI	CT with manual segmentation	EVAR
Murai [8]	2021	rAAA	CTA	EVAR + decompressive laparotomy
Wada [10]	2021	Trauma	CTA	TEVAR + SDH evacuation + lung partial resection

Abbreviations: AAA, abdominal aortic aneurysm; AAP, abdominal aortic pseudoaneurysm; AKI, acute kidney injury; CT, computed tomography; CTA, computed tomography angiography; EVAR, endovascular aortic repair; PMFSG, physician-modified fenestrated stent-graft; rAAA, ruptured abdominal aortic aneurysm; SDH, subdural hematoma; TEVAR, thoracic endovascular aortic repair; T1aEL, Type 1a endoleak.

[a] The diagnostic imaging was used to perform image fusion with fluoroscopy and digital subtraction angiography or cone-beam computed tomography.

Tables 1 and 2 provide the principal details of the included case reports and cohort studies.

3.2. *Case reports*

Masana Llimona et al [7] reported on a case of a 73-year-old man presenting to the emergency department with nonspecific symptoms and chronic kidney injury [7]. Because the first suspected diagnosis was pulmonary thromboembolism, thoracic CTA was performed and the patient subsequently experienced acute kidney injury (AKI) due to contrast-induced nephrotoxicity. Thus, when a ruptured abdominal aortic aneurysm (rAAA) was suspected, only noncontrast CT could be performed, which confirmed the presence of an AAA with a wide retroperitoneal hematoma. Endovascular aortic aneurysm repair (EVAR) was the first choice, given the patient's anatomic characteristics and AKI, and manual segmentation of the infrarenal aorta was performed, as the absence

Table 2 – Cohort studies selected from our research.[a]

Study, first author	Year	Diagnosis	IF technique	Treatment	Findings
Kaladji [16]	2015	AAA + eGFR ≤30 mL/min	CT + nonenhanced CBCT	EVAR, TEVAR	No endoleak, no eGFR decrease
Ahmad [14]	2019	AD, PAU, IMH, TAA, rTAA, and T1aEL	CTA + fluoroscopy	TEVAR	Reduced procedure and fluoroscopy time in the IF group
Tinelli [6]	2021	AAA and TAA	CTA + fluoroscopy	F-BEVAR	HOR group with three or more fenestrations/ branches: reduction of reinterventions and graft instability
Pruvot [5]	2022	EVAR	CTA + fluoroscopy	EVAR	HOR group: more accurate endograft positioning

Abbreviations: AAA, abdominal aortic aneurysm; AD, aortic dissection; CBCT, cone-beam computed tomography; CT, computed tomography; CTA, computed tomography angiography; eGFR, estimated glomerular filtration rate; EVAR, endovascular aortic repair; F-BEVAR, fenestrated/branched endovascular aortic repair; HOR, hybrid operating room; IF, image fusion; IMH, intramural hematoma; PAU, penetrating aortic ulcer; rTAA, ruptured thoracic aortic aneurysm; TEVAR, thoracic endovascular aortic repair; T1aEL, Type 1 endoleak; TAA, thoracic aortic aneurysm.

[a] None of the studies distinguished outcomes based on urgent or elective setting.

of contrast enhancement precluded automatic 3D reconstruction. The intervention was performed in an HOR and IF allowed matching of live fluoroscopic images with aortic segmentation images. Ten milliliters and 5 mL of contrast agent were needed to locate renal and hypogastric arteries, respectively, and final angiography with 15 mL of contrast agent was performed. One month later, the patient had recovered completely from the rAAA and AKI.

Murai et al [8] also reported on a case of rAAA, which was suspected when the patient arrived in the emergency department. Thus, the patient was brought directly to the HOR, where preoperative CTA was performed; time from clinical presentation to diagnosis was 25 minutes. EVAR was performed immediately on the same bed and lasted 106 minutes, including endovascular balloon occlusion positioning to stabilize vital signs and right hypogastric embolization. At the end, intraabdominal pressure was 36 mm Hg and a decompressive laparotomy was needed, which was also performed on the same bed, allowing intraabdominal pressure to decrease to 10 mm Hg and significant improvement of respiratory status. Because vacuum-assisted closure was required, the patient returned to the HOR 32 hours later for definitive abdominal closure.

Touma et al [9] presented a case of symptomatic AAA with a Type Ia endoleak, which was treated with in situ triple laser fenestration. The patient presented with acute abdominal pain and CTA was performed, revealing a Type Ia endoleak. The authors used IF to superimpose a 3D reconstruction based on preoperative CTA on images obtained with a periprocedural CBCT and aortic wall calcifications were used as landmarks. An aortic cuff (Endurant; Medtronic) was deployed, starting from the inferior edge of the celiac artery, and a steerable sheet (Aptus HeliFIX; Medtronic) was used to insert a laser catheter (Turbo Elite Excimer; Spectranetics) to perforate the graft. The fenestration was subsequently enlarged with a semi-compliant balloon and bridging stent-grafts were released. A single, final DSA was performed to assess technical success. The 6-month CTA showed resolution of the endoleak and the absence of target vessel or graft instability.

Wada et al [10] reported on a 46-year-old patient with life-threatening trauma after falling from height. The patient arrived with a Glasgow Coma Scale score of 3 and was immediately brought to the HOR, where a chest tube was inserted to resolve pneumothorax discovered on physical examination, and CTA was performed immediately, revealing an Azizzadeh grade III traumatic aortic injury [11], left lung contusion with active hemorrhage and hemopneumothorax, right subdural hematoma, and subarachnoid hemorrhage. Thirty-eight minutes after arrival in the emergency department, the subdural hematoma was evacuated and the upper lobe of the left lung was resected to control hemorrhage. Thoracic endovascular aortic repair (TEVAR) was then performed, with the need to cover the left subclavian artery. At this point, a novel brain CT was performed to monitor brain injury, which was stable. Because the pulmonary hemorrhage was still not resolved, the lower lobe of the left lung had to be resected. Diagnostic imaging (preoperative CTA and brain CT) and all interventions were performed in the same HOR, on the same bed, and without displacing the patient. After almost 6 hours of work, the patient was admitted to the intensive care unit and was discharged to a rehabilitation facility at month 5, with a Glasgow Outcome Scale score of 4.

Zeng et al [12] reported three cases of emergent vascular conditions treated using IF. The first patient presented with two abdominal aortic pseudoaneurysms and an infectious etiology was suspected. The second case was an AAA with radiologic signs of imminent rupture, and the third patient presented with an AAA and intense abdominal pain. All 3 patients underwent preoperative CTA and interventions were performed in an HOR with the implant of a physician-modified fenestrated stent-graft. In all cases, the preparation of the graft fenestrations was performed on a sterile field during the intervention, and the position of fenestrations was determined using the clock-face method. The physician-modified fenestrated stent-graft was ultimately deployed with an intraoperative IF technique, using the preoperative CTA and intraoperative fluoroscopy and DSA. All patients were successfully discharged home and 6-month imaging showed the correct graft positioning and absence of any target vessel or graft instability.

Finally, the report of Ziza et al [13] examined the case of an 83-year-old man with an rAAA and preoperative renal function impairment. The preoperative CTA was superimposed on the perioperative CBCT using aortic wall calcifications and soft tissues as landmarks. The EVAR procedure lasted 140 minutes, with 28 minutes of fluoroscopy time; required the injection of 30 mL contrast medium for the final angiography; and DAP was 400.5 Gy-cm^2. The 72-hour postoperative CTA excluded endoleak and the patient was successfully discharged home.

3.3. *Cohort studies*

Three of four selected articles divided patients into two groups based on whether the procedure was performed in an HOR with IF or in a standard OR; all authors analyzed outcomes without making a distinction between urgent and elective interventions.

Ahmad et al [14] analyzed the effect of IF with 2D/3D registration on reducing fluoroscopy time, procedure time, and contrast agent in patients undergoing TEVAR. The overall cohort of 146 cases was further divided into two groups: 98 patients to the IF group and 48 who underwent TEVAR without IF. There were 51 aortic dissections, 9 rAAAs, 6 penetrating aortic ulcers, 1 intramural hematoma, 1 Type I endoleak, and 78 elective thoracic aortic aneurysms. All procedures were performed in an HOR according to the ALARA (as low as reasonably achievable) guidelines on reducing contrast agent and radiation dose [15]. IF with 2D/3D registration was performed, overlaying the preoperative CTA with two single-shot fluoroscopy exposures with a difference ≥30 degrees. Overall, the IF group had a significantly lower dose of contrast medium (70 *v* 104 mL in the non-IF group; $P < .001$). The cohort was then further divided into a “simple” TEVAR subgroup, without any surgical procedure, and a hybrid TEVAR subgroup, with left subclavian artery coverage and left carotid–subclavian bypass. In the first subgroup, the IF group received less contrast agent, yet fluoroscopy and procedure time and radiation exposure did not differ. In the second subgroup, the procedure time was significantly reduced in the IF group (162 *v* 213 minutes in the non-IF group; $P = .015$), as was the fluoroscopy time (9 *v* 23 minutes in the non-IF group; $P < .005$), and DAP was similar between the two groups.

Kaladji et al [16] analyzed all patients undergoing EVAR who also had chronic kidney injury with an estimated glomerular filtration rate ≤30 mL/min/m^2. All 6 patients received had a preoperative nonenhanced CT scan performed, centerlines were achieved manually, and a specific software artificially enhanced the arterial axis. A nonenhanced CBCT was then performed intraoperatively and 3D/3D IF reconstruction was performed, which was ultimately superimposed on the 2D fluoroscopy. The authors performed 5 EVARs and 1 TEVAR without contrast medium. Technical success was confirmed with duplex ultrasound for AAAs and transesophageal duplex ultrasound for TEVAR.

The retrospective single-center analysis from Pruvot et al [5] included 93 patients undergoing infrarenal EVAR, who were further divided into an HOR group (49 patients) and a non-HOR group (44 patients). In all cases in the HOR group, technical success was verified with a nonenhanced CBCT and final DSA, or by means of contrast-enhanced CBCT. The primary end point was accuracy of endograft deployment by means of measuring the distance between the lower renal artery and the parallax of the proximal gold markers of the stent-graft (LwRA/EDG distance), which was introduced in a multivariate model. Furthermore, a composite “proximal neck”–related complications end point was presented, including endoleak or additional interventions during follow-up. Four emergent cases were included in the cohort, three of which in the HOR group. The endograft positioning was more accurate in the HOR group, with a shorter LwRA/EDG distance ($P = .022$), although no difference was detected during follow-up about the composite “proximal neck” end point.

Tinelli et al [6] performed a retrospective analysis of a multicenter prospective registry on fenestrated and branched EVAR performed in an HOR, comparing procedural short- and long-term clinical outcomes between the HOR group and the non-HOR group. In the HOR group, technical success was assessed with 2D DSA and noncontrast CBCT. The overall cohort included 262 patients, further divided as 133 patients treated in a standard OR with a mobile C-arm and 129 patients treated in an HOR. The contrast agent volume was decreased significantly in the HOR group ($P = .003$), as well as the DAP ($P = .009$), although the procedure time was augmented ($P < .001$). Target vessel instability and graft instability had a better trend in the HOR in the overall cohort, although it did not reach statistical significance ($P = .24$ and $P = .11$, respectively). Yet, if considering only the subgroup of complex fenestrated and branched EVAR (three or more fenestrations or branches), lower graft instability was observed in the HOR group ($P = .035$), as well as a lower rate of reintervention on target vessels (20% *v* 11.2% in the non-HOR group; $P = .019$) and of total reinterventions (24.4% *v* 15.5%; $P = .032$).

4. Discussion

MMI has traditionally been applied to the field of nuclear medicine, with the combination of CT and PET, or PET and single-photon emission computed tomography, providing both functional and anatomic information [2]. The application of MMI to vascular surgery is gaining popularity as a means to provide intraoperative guidance for endovascular interventions, usually performed in an HOR. There are several advantages to these particular surgical theaters. First, the replacement of image intensifiers with flat panels produces images with higher signal-to-noise ratio, thus of better quality and with reduced radiation levels [17,18], as also stated by the most recent European guidelines on radiation safety [19]. Asepsis is ameliorated, creating structures that avoid dust agglomeration and the environment is designed so multiple figures can work together as a multidisciplinary team [17], also allowing a rapid switch between diagnosis and surgical or endovascular procedures, without transferring the patient, which is fundamental especially in emergency situations. One of the most important tools of hybrid rooms is the IF technique, which can provide intraoperative guidance and allow immediate perioperative technical success assessment, possibly reducing the radiation dose and reintervention rate [17]. IF can be realized

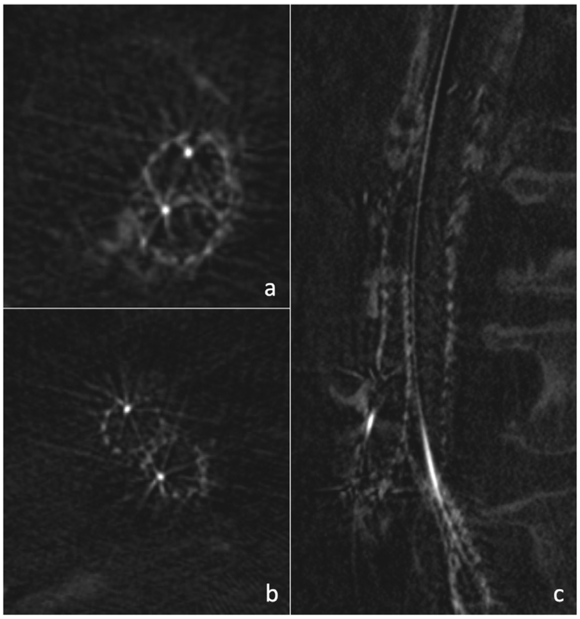

Fig. 2 – Cone-beam computed tomography performed at the end of a covered endovascular reconstruction of the aortic bifurcation. The image shows a transversal (a, b) and a coronal (c) view of the implanted stents.

with a 2D/3D or a 3D/3D reconstruction. In the first case, the preoperative CTA is overlayed on live fluoroscopy images, using bones (particularly two perpendicular views of the spine) as landmarks. In the 3D/3D reconstruction, the overlap is realized with the preoperative imaging technique and an intraoperative nonenhanced CBCT, although this technique normally requires a higher radiation dose [17]. The outcome visualization is a 3D reproduction of the arterial vessel of interest on the live fluoroscopy images [20]. CBCT also finds an application in direct puncture of vascular structures, tumor chemoembolization, or as a final control after an endovascular procedure [21]. In Figure 2, a non–contrast-enhanced CBCT verified the correct stent positioning after a covered endovascular reconstruction of the aortic bifurcation. The main limitation of CBCT is the possibility to scan only a restricted transverse section.

IF can be obtained with both manual and automatic techniques; the difference lies in bone alignment measurements, which can be achieved with two fluoroscopy images in the first case, and with one fluoroscopy image (anteroposterior) in the second case [22]. Smorenburg et al [22] compared the accuracy of both techniques, using bone alignment and vascular alignment as primary and secondary end points, respectively. The differences between the manual and automatic techniques for bone and vascular alignment were 0.1 mm and 0.6 mm, respectively, although the authors suggested future developments focus on automated correction of vascular alignment [22].

Many authors have explored the advantages of IF, especially in elective cases. Hertault et al [3] retrospectively analyzed 102 patients who underwent standard or complex EVAR in an HOR with IF and found significantly lower use of contrast agent and DAP. In their prospective observational trial, Maurel et al [23] found IF feasible both in HOR and in a standard OR with a mobile system, leading to a 50% reduction in radiation dose, and suitable in every center, even if an HOR is not economically affordable. Although these results are optimal, we do believe that they can be achieved after a proper period of training, which is mandatory before performing emergent interventions in an HOR. In fact, future literature could focus on a learning curve analysis because this information could be interesting for those centers that are considering HORs. Image workstations used in HOR can also be employed in the preoperative planning because device sizing can be facilitated by means of automated vessel analysis [17]. Furthermore, some authors [17] have started to focus on the role of artificial intelligence. In fact, future developments could allow the automation of selected parts of procedures, using surgical robots, so that the operator can perform the intervention from the control room, or even from another center [17].

In addition to IF with CTA, CBCT, and fluoroscopy, other tools can be applied to the field of MMI in vascular surgery. Some authors [24,25] have highlighted the added value and benefits of intravascular ultrasound during aortic endovascular procedures, especially in sizing, planning, intraoperative guidance, and also bridging stent-graft patency and positioning assessment in branched EVAR. An IF could also possibly be performed with carbon dioxide angiography, as its capacity to reduce contrast media use has been demonstrated in other arterial districts [26]. Finally, Finnesgard et al [27] recently introduced their initial experience with Fiber Optic RealShape (FORS) guidance in fenestrated and branched EVAR procedures [27]. FORS is a novel technique that enables 3D visualization of endovascular material without the need for fluoroscopy. The authors [27] compared 21 FORS-guided procedures with 61 non–FORS-guided procedures and found that procedure and fluoroscopy times were lower in the first group.

In this review, our goal was to report the literature on the currently available experience with MMI in diagnosis and treatment in vascular surgery, focusing on emergent conditions. Despite the diffusion of IF use in an elective context, reports in emergency settings are limited. This review included 10 articles, 6 of which were case reports. Nevertheless, we believe that the usefulness of IF and HOR has emerged. Three groups of authors have reported their experience with rAAA [7,8,13]; in one case the preoperative CTA was performed in the HOR [8], where the patient subsequently underwent EVAR using IF and decompressive laparotomy, highlighting the usefulness of a hybrid angio-surgical suite in reducing the time from diagnosis to effective intervention, not having to move the patient, and saving time. Wada et al [10] reported a case of major trauma, where diagnosis and treatment performed by a multidisciplinary team involving vascular surgeons and neurosurgeons were performed in the same room, again without patient displacement. The utility of a dedicated hybrid trauma OR has previously been reported in a retrospective cohort analysis of 292 patients undergoing immediate surgery at a level 1 trauma center. This type of angio-surgical suite was associated with rapid and earlier hemorrhage control, reduction in infectious rate, and a reduction in ventilator days [28].

In Kaladji et al [16], observational study, patients presented with a severe renal function deterioration, yet the use of IF between a preoperative nonenhanced CT and intraoperative nonenhanced CBCT allowed 5 EVAR and 1 TEVAR to be performed without any contrast agent; technical success was assessed with duplex ultrasound. We believe that this report is one of the best examples of MMI application in challenging settings, especially focusing on AKI prevention.

Tinelli et al [6] reported on complex aortic procedures and highlighted that, even on the long term, patients who underwent procedures in an HOR with IF, experienced a lower rate of graft instability and reinterventions, both overall and target vessel-related.

Despite the unequivocal advantages, some authors believe that IF could present one major limitation related to vessel deformation due to the insertion of rigid guidewires and catheters, especially at the level of iliac arteries, which could lead to a lack of precision in images overlapping [20,29–32]. Furthermore, some authors have also questioned cardiac and respiratory movements, although these seem to be limited (displacement <2 mm) [20]. Nevertheless, for this purpose, some groups have started to develop a predictive model of vessel deformation using finite element simulation, which could be applied during intraoperative IF [33,34].

The main limitation of this review was the fact that we could only perform a narrative synthesis and, most importantly, the absence of cohort studies that were focused specifically on emergent conditions. Furthermore, available data about urgent interventions were only related to the application of MMI in HORs with the use of CTA, CBCT, and fluoroscopy. However, because the field of MMI with multiple imaging tools is rapidly evolving, future studies could focus on the role of carbon dioxide angiography, FORS, and intravascular ultrasound also in emergent conditions.

5. Conclusions

Vascular surgeons often deal with emergent situations and interventions are performed increasingly by endovascular means or with hybrid procedures. The utility of IF in reducing contrast media and radiation dose in elective standard or complex endovascular aortic repair has often been reported. Although limited to case reports and non–emergency-specific cohort studies, this review highlighted the potential of IF in hybrid angio-surgical suites for emergency vascular conditions, especially for allowing diagnosis and treatment in the same operating room, avoiding patient transfer, and permitting procedures be performed with zero or low-dose contrast mean.

Studies with a larger number of patients and comparing intraoperative data and clinical outcomes between patients treated in emergency conditions in standard and hybrid operating rooms are advisable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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